Interactive comment on Variability of cirrus cloud properties using a Polly^{XT} Raman Lidar over high and tropical latitudes" by Kalliopi Artemis Voudouri et al.

Anonymous Referee #2

In the study discussed below, the authors around Kalliopi Artemis Voudouri present a cirrus cloud statistics for several sites where a multi-wavelength Raman lidar system of type Polly-XT was deployed.
The lidar data was analyzed with a newly developed cirrus retrieval algorithm. Cloud boundary detection was based on wavelet transformation of a kind of normalized background-corrected raw signals. For the identified cirrus layers cloud optical properties for 355-nm and 532-nm wavelength were derived and a multiple-scattering correction was applied. The derived statistics of geometrical and optical cirrus cloud properties are diverse.
Clear conclusions could not be drawn.
I see a certain strengths in the manuscript, given the following facts:
- Presentation of a newly developed cirrus cloud identification algorithm
- Retrieval of Raman-based cirrus optical properties for 355 AND 532 nm
- Demonstration of the potential of a network of similar Raman lidar systems for application of one single retrieval scheme

Nevertheless, flaws in the description of the data analysis technique and in the discussion of the statistics dominate my impression while I was reading (several times) through the manuscript. I felt uncomfortable reading through the results section without knowing exactly how the statistics were derived.
"Cases" are presented, but how is one case defined?

See our comment on answer number 13.
To how many cloud profiles was the wavelet transform applied to get the boundaries?

See our comment on answer number 1.
Are the presented optical properties based on Raman or Klett?

See our comment on answer number 11.

These are important questions. Without knowledge about these, the value of the study is very limited.

I thus recommend a major revision of the manuscript, including a second review phase in order to put the study on a more solid footing.

We thank the reviewer for his/her remarks that helped us to improve the manuscript. In the revised version the reviewer's comments have been extensively taken into account, by improving the discussion of many sections (i.e., algorithm, comparison among the different stations) and by improving the figures that lacked of an accurate description. Moreover, parts of the paper have been restructured and all the figures have been reprocessed, as in the present form is not easy to follow the comparisons of the cirrus properties between the different sites.

Below we report the changes included in the revised manuscript as a response to the comments of the reviewer.

Major comments:

1) 1 – Ch.3; Retrieval Scheme/Fig. 1:

The presentation of a retrieval scheme should always be done in such a way that others are able to reproduce it. The scheme given in Ch. 3 does not allow for that, because important information is missing:
o Was there range-averaging applied? If yes, under which conditions (see e.g. Fig. 1 b vs. 1 c)
o What happened to 1-hour intervals not filled entirely by cirrus clouds?

How were irregularities in the cirrus cloud structure within the 1-hour averaging period treated?

The reviewer is right that is difficult to follow the algorithm steps with Figure2, as the time averaging presented is different. In the revised version of the algorithm however, we reprocessed the data and Figure 3 presents the 1-hour averaged profiles.
To calculate the cirrus boundaries, the code applies the following steps:

i) The wavelet covariance is calculated for every single profile (every 30s).
ii) The profiles that fulfil the criteria for a cirrus detection (Figure 2, schematic flowchart) are hourly averaged.
(iii) A mean value of the cirrus base and top are attributed to the one- hour processing. Nan values (free of cirrus sets) are not computed to the mean boundaries.

We also calculate the differences within an hour between the bases/top calculated for every 30s profile, and these should not exceed the 0.5km. If differences are greater than this value, we exclude the case. With this assumption, we also exclude cases with large variability of cirrus layers.

2) "the signal is normalized with a maximum value below 1.5km". What does this mean?
Was the signal normalized using the maximum value found between the ground and 1.5 km height (or range)?

The normalization is applied to ensure the applicability of the method (the threshold critiria for cirrus boundaries) to all the lidar systems. Given that lidar signals are uncalibrated and signal levels from one lidar system to another can be rather different, the normalization ensures the applicability of the criteria used by Baars et al., 2008. We normalized the range-corrected signal by its maximum value found below 1500 m. (below 2500 for Elandsfontein), which is usually the maximum value of the range corrected signal within the Boundary Layer, as proposed by Baars (2008), in order to use the same threshold values for the cirrus boundaries.

3) In Eq. (1): What is z? altitude or range? Is this z the same z as the one in Eq. 3?

I fear that range and height are mixed-up somewhat. Introduce separate variables for height and range where applicable/needed. Also: Is altitude above ground or above sea level (asl)? Was this considered in the statistics (given that the station elevation varies from 190 to 1745 m asl)?

Yes, the altitude in all plots corresponds to height above sea level, and this is considered in the statistics.

4) Eq. 2: What is Csig? Raw signal? Counts? What is Cbg? What is the difference between C and P (Eq. 1 vs. Eq. 2)?

C stands for the lidar raw signal, while P is the signal after applying the SNR filter, the background correction, the range correction and the normalized correction. That is the reason for using different symbols.

5) Case study/Fig. 2: The case study spans over about 4 hours, but the standard averaging period to derive the wavelet and particle depolarization ratio was 1 hour, wasn't it? I propose to show a case study that uses the actual time- and range-resolution used in the cirrus retrieval scheme.

The reviewer is right. In the revised version of the paper we revised Figure 3, with the hourly application of the cirrus retrieval scheme to the case study.

6) According the Figure 1, zero and background levels as well as normalization were applied to the range-corrected signal. Is this true? Shouldn't at least the background and zero values be subtracted from the raw signal?

We firstly applied the threshold for the SNR, we then corrected the signal for the zero and background, we calculated the range corrected signal and finally, we applied the wavelet.

7) The selected base temperature of <-20°C (see Fig. 1) gives risk to the inclusion of layers of supercooled liquid water into the statistics, as ice formation occurs pre-dominantly via the liquid phase at T<-27°C (Westbrook et al., 2011). Was there any threshold put on the temperature at cloud top? I'd believe a good value for this could be -38°C or so in order to assure that at least at cloud top no liquid water was present any more.

The reviewer is right. In the revised version of the manuscript we applied an additional criteria for classification, regarding the top temperature in our data processing. So, in Figure 2 the schematic flowchart has been changed with the new threshold applied to the top temperature and also all figures have been reprocessed, according to this new value.
We also modified the paragraph in the revised version, which now reads: "Finally, cloud retrievals from the algorithm are classified as cirrus clouds when the following four criteria were met: i) the particle linear depolarization value is higher than 0.25 (Chen at al., 2002; Noel et al., 2002), ii) the altitude is higher than 6km and iii) the base temperature is below -27°C (Goldfarb et al., 2001; Westbrook et al., 2011) and iv) the top temperature is below -38°C (Campbell et al., 2015)."

Campbell, J. R., Vaughan, M. A., Oo, M., Holz, R. E., Lewis, J. R., and Welton, E. J.: Distinguishing cirrus cloud presence in autonomous lidar measurements, Atmos. Meas. Tech., 8, 435– 449, doi:10.5194/amt-8-435-2015, 2015.

8) In Fig. 1: Again, what is altitude? Above sea level?
Yes, the altitude corresponds to altitude above sea level.

9) In Fig. 1: Particle linear depolarization ratio is used as criteria for cirrus classification. But this parameter requires the detection of particle backscatter coefficient first.
Shouldn't Fig. 1 thus contain an additional column (between CWT and cirrus criteria) that describes the calculation of the optical properties and multiple-scattering correction?

Yes, the reviewer is right. We revised Figure 3, with the hourly application of the cirrus retrieval scheme to the case study and we also added the hourly backscatter profile.

10) In Fig. 2: Why do the cloud boundaries differ between (b) and (c)? Was there vertical smoothing applied to (c)?

Yes, they differ due to the different time averaging and also to the smoothing applied to the optical properties. In the revised version of the manuscript, we changed smoothing to more strict ones and we reprocessed the figure with the hourly application of the wavelet and the hourly retrievals.

11) - Cirrus optical properties:
- During daytime, Klett-Fernald was applied, and during nighttime Raman was applied?
Which values went into the statistics of lidar ratio, optical depth and particle depolarization ratio? Both? Only nighttime?

Yes, the reviewer is right. Both values from the two methods are presented in the statistics presented. However, in the revised version, Table 2 and Table 3 have been added, giving the information of the different geometrical and optical values derived from the two methods. See also comment on answer 13.

12) How were reference height and values determined/set?

The determination of the reference height range in the PollyXT software, is made as follows (Baars et al., 2016):
– the user determines the reference height range (zref) from the quicklook of the range corrected signal and provides the sounding file.
– the code calculates the Rayleigh fits (Freudenthaler, 2009) for several zref
– assesses the determined zref
– finds the optimum zref

A similar method is applied in the Single Calculus Chain algorithm for the backscatter calibration (Mattis et al., 2016). In this method, it is also assumed that the height range provided by the user, where the signal or signal ratio has its minimum is closest to the assumed particle-free conditions.

Baars, H., Kanitz, T., Engelmann, R., Althausen, D., Heese, B., Komppula, M., Preißler, J., Tesche, M., Ansmann, A., Wandinger, U., Lim, J.-H., Ahn, J. Y., Stachlewska, I. S., Amiridis, V., Marinou, E., Seifert, P., Hofer, J., Skupin, A., Schneider, F., Bohlmann, S., Foth, A., Bley, S., Pfüller, A., Giannakaki, E., Lihavainen, H., Viisanen, Y., Hooda, R. K., Pereira, S. N., Bortoli, D., Wagner, F., Mattis, I., Janicka, L., Markowicz, K. M., Achtert, P., Artaxo, P., Pauliquevis, T., Souza, R. A. F., Sharma, V. P., van Zyl, P. G., Beukes, J. P., Sun, J., Rohwer, E. G., Deng, R., Mamouri, R.-E., and Zamorano, F.: An overview of the first decade of Polly^{NET}: an emerging network of automated Raman-polarization lidars for continuous aerosol profiling, Atmos. Chem. Phys., 16, 5111–5137, https://doi.org/10.5194/acp-16-5111-2016, 2016.

Freudenthaler, V.: Lidar Rayleigh-fit criteria, in: EARLINET-ASOS 7th Workshop, available at: http://nbn-resolving.de/urn/resolver.pl?urn=nbn:de:bvb:19-epub-12970-6 (last access: 11 February 2015), 2009.

Mattis, I., D'Amico, G., Baars, H., Amodeo, A., Madonna, F., and Iarlori, M.: EARLINET Single Calculus Chain – technical – Part 2: Calculation of optical products, Atmos. Meas. Tech., 9, 3009–3029, https://doi.org/10.5194/amt-9-3009-2016, 2016.

13) In the results section, there should be a discussion of Klett-vs-Raman-based results.

Table 2 in the revised version of the manuscript, shows the average cloud base and top altitudes and the average geometrical thickness for each site separating daytime and nighttime measurements. The averaged geometrical properties are found to be nearly identical above all sites, with differences less than 0.2km. Table 3 shows the averaged lidar ratio values, which found to be nearly identical above all except Gual Pahari site where average nightttime LR is 4sr higher than that of daytime.
"Table 2 summarizes the mean geometrical values calculated for each site. Differences between the mean values of the geometrical properties in the daytime and nighttime measurements are less than 200m for all sites."
"Table 3 summarizes the mean optical values discussed above, for the three sites, separating daytime and nighttime observations. Generally, the averaged optical properties values are found to be nearly identical, except one site (New Delhi), where average nighttime optical properties found higher than that of daytime. But since this dataset is limited, it cannot be used as a reference one."

14) - Ch 4.02 Multiple Scattering correction:
- The lidar observations provide Ptot, but P1 is required. Eq. 4 thus contains 2 unknowns: P1, and F(z). How could the authors solve this equation?

To calculate the multiple scattering correction, the code applies an iterative method including the following steps:
i) The measured extinction profile of the cirrus layer is provided.
ii) With the provided effective radius profile of the cirrus layer (linear relation of the effective radius with the cirrus temperature derived from radio soundings) and the effective (measured) extinction coefficient α par (z), the model provides the ratio P (z)/P (1) (z).
iii) From (2) a first value for the correcting factor F(z) can be worked out.
iv) The iterative procedure continues till the calculation of a stable correcting factor F(z) is found.
v) The corrected extinction can be then calculated from equation (5) in the manuscript and hence the value of lidar ratio.

15) – Ch. 5.01 Cirrus cloud cover detection:
- How is a case defined? What does it mean if there were 28 cases observed over Kuopio in April (P7, L175)?

A case is defined as an hourly case. The algorithm searches every set and the ones that fulfill the criteria for cirrus detection, are hourly averaged. See also comment on question 1.

16) Table 2: What is N? Are these the number of hourly samples?

Yes, these are numbers of hourly samples.

17) – Ch. 5.05:
The title can be modified to 'cirrus classification at Kuopio' because the section only deals with this site.

The reviewer is right. In the revised version of the manuscript this paragraph has been changed and the title of the Section 4.0.4 is "Cirrus classification at Kuopio".

18) – Ch. 5.06, Line 321:
Could the decrease of particle LDR with increasing temperature be explained by the sporadic presence of supercooled liquid water?

Generally, the decreasing particle LDR with increasing temperature is believed to reflect the gradual change in basic ice crystal shape, from plates to columns (Noel et al., 2002). Weitkamp also reported that the presence of supercooled water droplets in cirrus is uncommon. Maybe a combination of cloud radar and lidar retrievals can give as more information.

Lidar. Range-Resolved Optical Remote Sensing of the Atmosphere, in the Springer Series in Optical Sciences, edited by Claus Weitkamp

19) - Conclusions:
- What conclusion can be drawn on the conversion of cirrus optical properties from 532 nm to 355 nm, considering that such conversion factors might be required to make future 355-nm/532-nm spaceborne lidar observations comperable? Can the authors make suggestions on which aspects future studies should look in more detail?

The assumption that the backscatter and the extinction coefficients for sufficiently large cirrus particles are spectrally independent; that is, the ratio of cloud backscatter coefficients and the ratio of cloud extinction coefficients will both equal unity, is well established (Reagan et al, 2002) and used in satellite processing schemes. But, it is also reported that the measured variability of cirrus color ratios is much larger than previously realized and that measured color ratios are higher in the tropics (Vaughan et al., 2010). From this study, mean values of LR and COD values in Figure 3 can indicate that there is not a significant spectral dependence, derived from groundbased dataset and differences are mainly found to the extinction profiles (also reported by Haarig et al. 2016). Reasons for that deviations could be either an increase in the MS effect with decreasing wavelength, or that the cirrus crystal size distribution could cause stronger extinction at 532 than at the shorter wavelength of 355 nm, or to the different saturation inside the cirrus layer. Figure 11 presenting the color ratios values on 5°C intervals of cirrus mid temperature, indicate an almost stable behavior with temperature. Generally, we can conclude that for higher altitudes, lower spectral dependence is noticed, taking also into account the number of measurements performed at each site. For the Kuopio station, mean BAE is found 1.1±0.9, while for the less extensive dataset of New Delhi the mean value is found 1.5±0.8 and for Elandsfontein the mean value is 1.4±1.1. So, maybe a more representative dataset in the tropics, should be used in order to conclude about the spectral dependence in these regions.

Reagan, J. A., X. Wang, and M. T. Osborn, Spaceborne lidar calibration from cirrus and molecular backscatter returns, IEEE Trans. Geosci. Remote Sens., 40, 2285–2290, 2002.

Vaughan, M. A., Liu, Z., McGill, M. J., Hu, Y., and Obland, M. D., On the spectral dependence of backscatter from cirrus clouds: Assessing CALIOP's 1064 nm calibration assumptions using cloud physics lidar measurements, J. Geophys. Res., 115, D14206, doi:10.1029/2009JD013086, 2010.

In addition to the points addressed above, I recommend a thorough peer-review of spelling and grammar by the co-authors in beforehand to the submission of the revised manuscript.

- Minor comments will be addressed in the revised version.

References:

Westbrook, C. D., and Illingworth, A. J. (2011), Evidence that ice forms primarily in supercooled liquid clouds at temperatures > −27 ∘ C, Geophys. Res. Lett., 38, L14808, doi:10.1029/2011GL048021.